NASA/TM-20220001811

Pumpless Particle Seeder for PIV Applications to High-Pressure Flows

Mehti Koklu
Langley Research Center, Hampton, Virginia

June 2022

NASA STI Program Report Series

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

- Help desk contact information:

https://www.sti.nasa.gov/sti-contact-form/
and select the "General" help request type.

NASA/TM-20220001811

Pumpless Particle Seeder for PIV Applications to High-Pressure Flows

Mehti Koklu
Langley Research Center, Hampton, Virginia

National Aeronautics and
Space Administration

Langley Research Center
Hampton, VA, 23681

June 2022

Abstract

A new particle seeder was designed for high-pressure airflows, which are known to be challenging to seed. The new seeder is similar to a standard fog machine and works based on the condensation principle. The new design is very simple and can easily be incorporated into an experimental set-up. A sample seeder was built using readily available parts in the laboratory. The design includes a heater element and a reservoir for the fog fluid. A wick was used to transport fog fluid to the heater element; therefore, the design does not require a pump. The feasibility of the seeder was demonstrated by a series of tests. First, the particles generated by the seeder were analyzed using a spectrometer, and the results were compared to those of a commercial fog machine. The spectrometer result indicated that the seeder produced particles with a typical diameter of 1 micrometer. Next, the seeder was attached to a fluidic actuator that produced a high-speed jet. Particle image velocimetry was used to test the capability of the seeder by measuring the steady and oscillating jet flow fields out of the fluidic actuator. The results indicated that the new seeder may be a viable option for seeding the high-pressure airflows to enable visualization and particle-based measurement techniques.

Introduction

There are many particle-based techniques available to the research community to enable nonintrusive investigating of complex flows. These techniques rely on scattered light from the tracer particles that are illuminated by a laser sheet. The illuminated tracer particles are imaged and then the images are postprocessed to calculate the velocity of the flow being studied. These methods either track the individual particles along the trajectory (particle tracking velocimetry [1]) or track the particles passing an observation point (such as particle image velocimetry [2] and laser doppler velocimetry [3].) The accuracy of the velocity information is limited by the particles' ability to scatter light and follow the instantaneous fluid motion [4]. As such, the particles should be large enough to scatter sufficient light but small enough to follow the fluid motion without changing the character of the fluid.

Appropriate seeding is particularly important in particle image velocimetry (PIV). The PIV technique provides two or three components of velocity by measuring the displacement of the particles using image correlations. Therefore, a sufficient number of particles are needed throughout the measurement area to resolve the particle displacement accurately. In addition, a uniform particle size is desirable in order to avoid excessive intensity from larger particles [4]. Many methods have been developed to generate seeding particles for airflows. The seeding particles can be in the form of liquid droplets or solid particles. The liquid droplets can be generated by condensation (e.g., fog machine) or atomization (e.g., Laskin nozzle), whereas the solid particles can be generated by atomization or from powders (e.g., fluidized bed). Each method has advantages, which are summarized in Ref. [4].

The most common seeding method for airflows is fine liquid droplets, like fog or smoke, generated by condensation. In its basic form, the fog fluid is evaporated by a heating element and the vapor condenses into fine droplets (fog) in the airflow. Most of the theatrical fog machines or smoke generators work based on the condensation principle. Mineral oil, propylene glycol, or a glycerin and water mixture are commonly used in the fog machines to generate fog or smoke. Although there are different types, a fog machine basically consists of a fluid reservoir, a pump, and a heater element (Fig. 1a). An electronic controller unit can also be used to regulate the pump and the heater. The pump moves the fog fluid from the reservoir to the heater, where the fog fluid vaporizes into forms of fine particles. These types of fog machines are commonly used for PIV measurements in wind tunnels.

High-pressure flows can be found in many engineering systems such as nozzles, ejectors, injectors, combustors, etc. Here, high-pressure flows refer to jet flows injecting into a surrounding

medium at rest or in motion. Introducing seeding particles into higher-pressure flows is known to be challenging [5]. If the jet flow is not seeded, then there will not be enough signal (scattered light) for velocity measurements. In addition, if the flow outside the jet is seeded, the jet flow will displace the seeded flow, again resulting in an insufficient number of particles. Reference [5] highlights some specific issues encountered when attempting to seed a high-pressure flow for PIV and the effect of sparse seeding. In situations where the high-pressure system is large enough, the seeder can be installed inside the high-pressure system. The only problem remaining is that the seeder should be able to provide seeding at elevated pressures. If the high-pressure system is not large enough, as in the case of most lab scale applications, then the higher static pressure presents practical problems for injecting the particles into the jet flow. This is because the output of a standard fog machine is not pressurized.

Laskin nozzles (or fluidized beds for solid particles) are usually ideal seeding methods for the higher-pressure systems as they use compressed air to generate particles. However, as indicated by Melling [4], the Laskin nozzle type seeders produce a polydisperse spray, and may require an impactor to remove the larger droplets. These large droplets not only cause excessive intensity but also accumulate inside the high-pressure systems generating unexpected flow behavior. In addition, since the Laskin nozzles require compressed air that has higher pressure than the working flow, it will change the pressure and mass flow characteristics of the working flow. Although a new type of Laskin nozzle seeder with a venturi effect was developed for high-pressure systems (such as the booster separation motors) [6] and further improved in Ref. [7], these two problems still persist. Given the disadvantages of the Laskin nozzles type seeders, the objective of this paper is to present a simple method for seeding the higher-pressure flows with condensation type seeders.

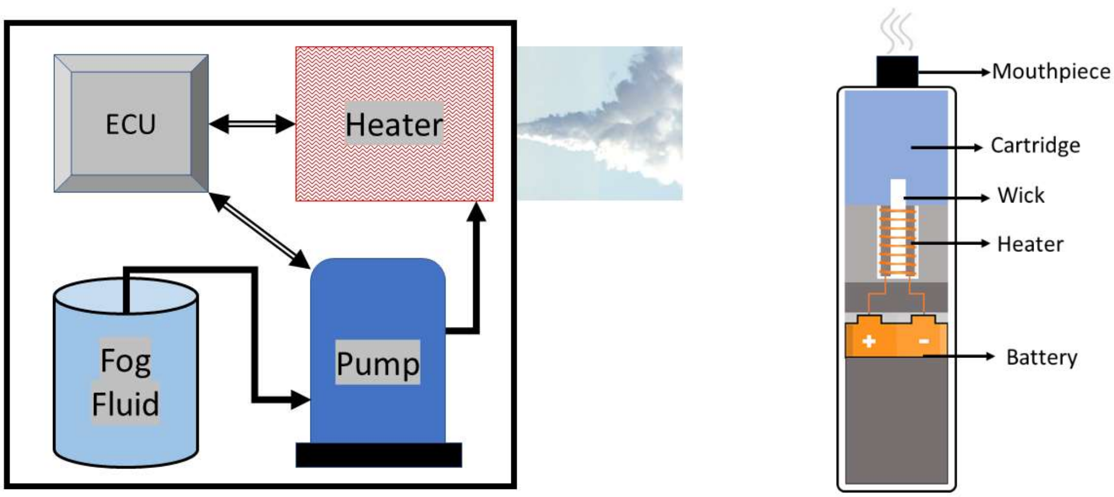
Method and Apparatus

In order to seed high-pressure flows and to enable PIV or other particle-based measurement techniques, a simple fog machine was designed. As mentioned, the condensation type seeders, such as fog machines, are commonly used to seed wind tunnel flows. The main problem of seeding high-pressure flows is that standard fog machines are usually larger than the high-pressure systems. Therefore, it is difficult to install a fog machine inside the high-pressure system to seed the flow. The main parts of a fog machine are the heater element to vaporize the fog fluid into the fine mist of particles, a reservoir to house the fog fluid, and a pump to transport fog fluid from reservoir to the heating element at desired amount. To overcome the challenges in introducing the seed particles into the higher-pressure flows, all three parts should be incorporated into the high-pressure delivery system. This way, there will not be a pressure difference between the injection mechanism for the particles and the high-pressure system. In addition, the fog machine should have minimal moving parts to keep the system as simple as possible.

Maeres et al. [5] showed a simple and inexpensive solution to seed high-pressure airflows by burning smoke pellets. On the other hand, Hamdi et al. [8] used cigarette smoke as seeding in electrohydrodynamic applications. Likewise, one can also use e-cigarette smoke as seeding particles. As shown in Fig. 1b, an e-cigarette is in fact a small fog machine. It basically consists of a coil (heater element), cartridge (reservoir), a wick (pump), and a battery (power supply). The most attractive feature of the e-cigarette design is its small size; therefore, it can easily fit into any high-pressure systems. In addition, an e-cigarette uses the same materials, such as propylene glycol, to produce smoke. Another attractive feature is that it has no moving parts (i.e., pumpless) where it uses a wick to transport the fog fluid to the heater.

A sample seeder design that is motivated by e-cigarettes is shown in Fig. 2a. In this design, the seeder unit is part of the high-pressure system; therefore, it does not change the flow rate or the pressure of the airflow. The seeder consists of a reservoir, a heater element, and a wick. One

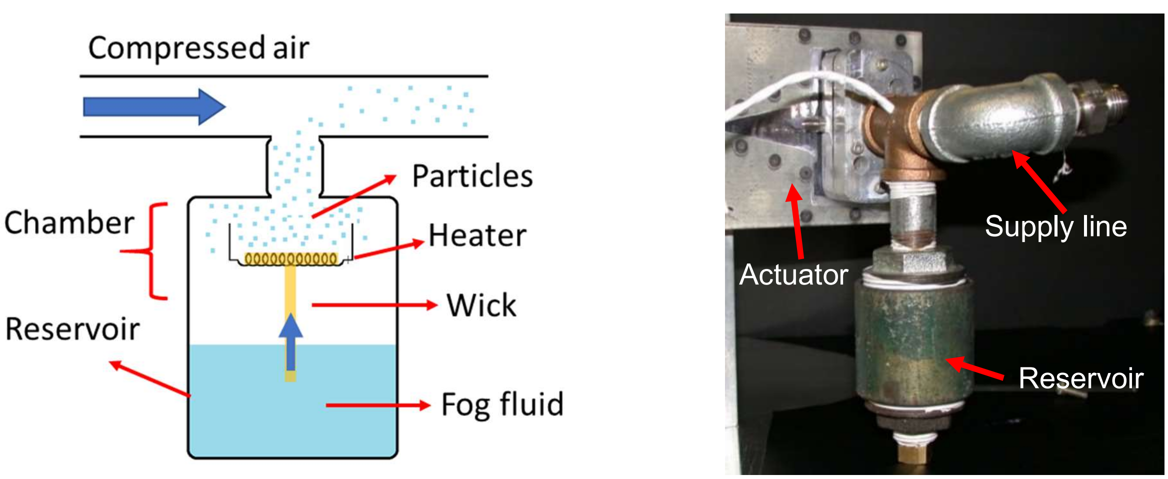
end of the wick is inserted into fog fluid while the other end is attached to the heater element. The wick is made of fiberglass; therefore, it is not burned by the heater. The fibrous structure of the wick material causes a capillary force that transports fog fluid from the reservoir to the heater element. When a DC current passes through the heater element, it vaporizes fog fluid around the heater element. Vaporized fog fluid (i.e., particles) is entrained by and mixes into the airflow. The process continues as vaporized fog fluid is replaced by the fresh fog fluid that is transported by the wick.



(a) Fog machine **(b) Electronic cigarette**

Fig. 1. Schematics of a typical (a) fog machine and (b) electronic cigarette.

This simple seeder can be built using readily available parts in a laboratory. A sample unit is shown in the Fig. 2b. In this design, the seeder was connected to the high-pressure supply line that goes to the fluidic actuator. The reservoir was constructed using a four-inch diameter metal pipe. One end of the pipe was capped, and the other end was attached to the supply line via a Tee fitting. The reservoir was filled with propylene glycol as fog fluid. A fiberglass rope was used as a wick. A NiCr wire was wrapped around the fiberglass rope and acted as a heating element. Although the heating element is not shown, it is similar to the description in Fig. 2a. The Tee was drilled to connect the heater element to a DC power supply.

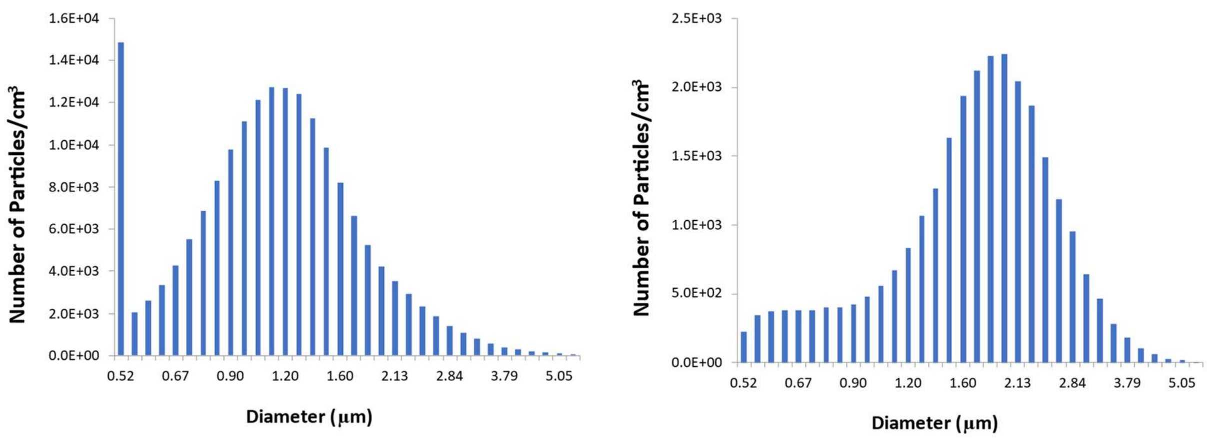


(a) Seeder design schematic **(b)As-built seeder**

Fig. 2. Seeder design (a) schematic and (b) photo.

Results

Before presenting the sample PIV results, which demonstrate the capability of the seeder, the size and concentration of the generated particles will be assessed. The size and concentration were measured using a commercial spectrometer (or particle analyzer). The antistatic hose of the spectrometer was placed downstream of the seeder. The seeder was turned on, and the sample particles from the seeder were collected. The spectrometer provided the aerodynamic diameter of particles and their relative concentration for particle diameter between 0.5 μm and 20 μm. The histogram of the aerodynamic particle diameters is presented in Fig. 3a. Note that the number of particles presented in this histogram is not the maximum output of the seeders. As shown, the particles have a gaussian distribution with a typical diameter of 1.2 μm. The spectrometer was unable to determine diameters below 0.5 μm; therefore, we see a large peak near 0.5 μm. The particles produced by a commercial fog machine (seeder) were also analyzed in a similar manner, and the results are compared. The commercial seeder produced particles about 2 μm in diameter.



(a) **(b)**

Fig. 3. Particle size distributions of (a) the present seeder and (b) a commercial seeder.

Figure 4 shows a representative particle image produced using the seeder where high-pressure flow (jet flow from a fluidic actuator) was injected into a lower pressure (ambient) flow. For this configuration, the test section of the NASA Langley 15-Inch Wind Tunnel was used to construct the ambient environment without running the tunnel. The fluidic actuator was mounted at the center of the wind tunnel and blowing right to left. The wind tunnel was seeded using a commercial seeder, whereas the jet flow out of the fluidic actuator was seeded using the present seeder. As shown in Fig. 4, the laser illuminated particles appear uniform and the difference between the particles from the two different seeders is indistinguishable in this raw image.

The statistical results from the spectrometer and the uniformity of the particles in the raw particle image show the viability of the present seeder. The next step is to assess the capability of the seeder in obtaining qualitative information using PIV. First, the flow field of a steady jet flow was investigated. The fluidic actuator reported in Ref. [9] was operated in the steady mode to generate steady jet flow into the quiescent environment. The mass flow rate of the actuator was controlled by the flow meter and held constant (0.01 lb./s) during the experiment. The present seeder was installed between the actuator and the flow meter as shown in Fig. 2b. Polyethylene glycol was used as the fog fluid to produce seeding particles. The PIV system included a 1024x1280 CCD camera installed with a 105 mm Macro lens and a double pulse Nd-Yag laser. An interrogation window size of 32x32 pixels with 50% overlap was used. The image pairs were processed using a commercial PIV cross-correlation algorithm [10] to give instantaneous velocity fields and then averaged to give the mean velocity field.

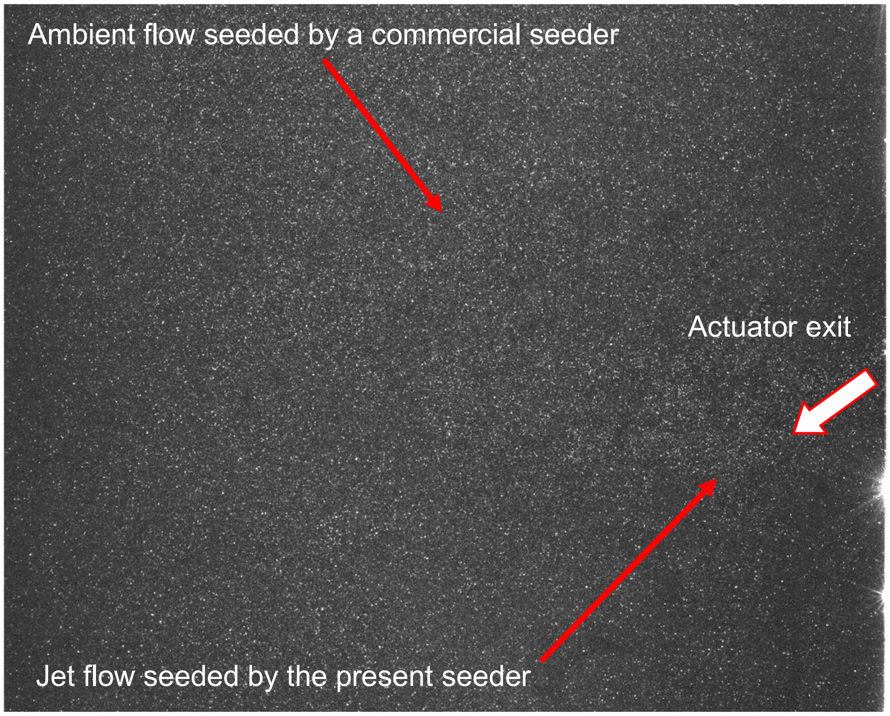
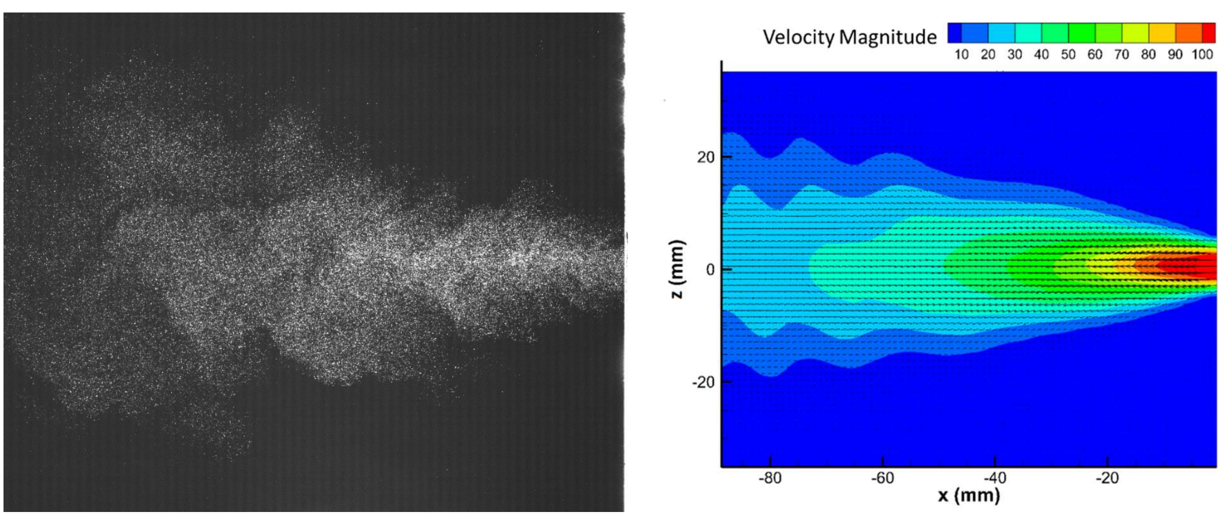


Fig. 4. Comparison of the particles generated by the present seeder and a commercial seeder.

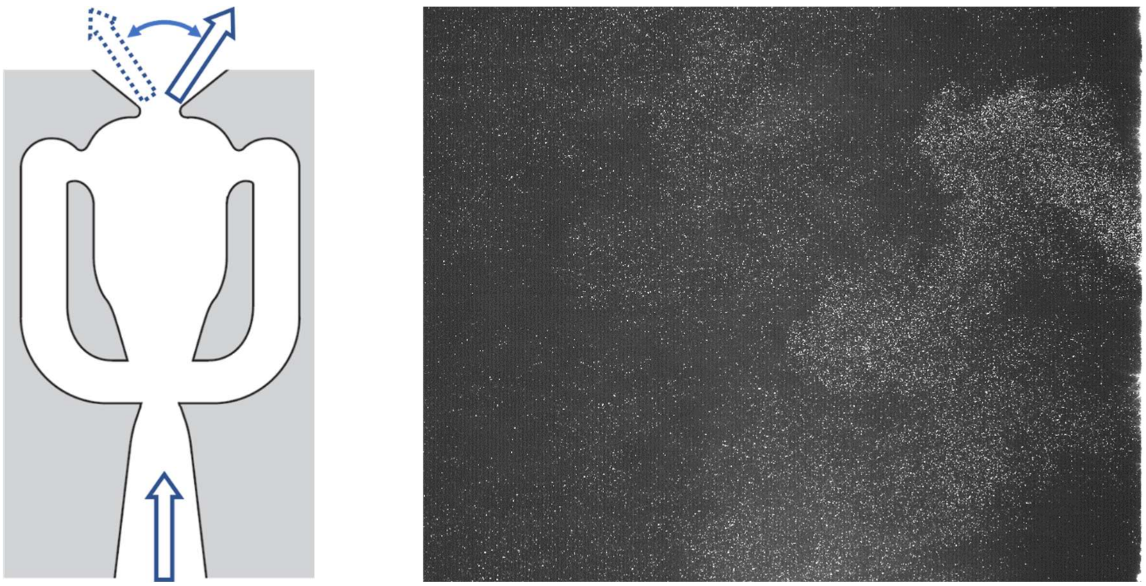
Figure 5a shows the illuminated particles emitting from the fluidic actuator. The jet flow is from right to left. The particles appear globally symmetric along the centerline; however, the unsteady flow structures in the shear layer are observed. As typical, jet flow entrains fluid from the ambient environment and spreads in the traverse direction. Therefore, we see fewer particles downstream. The figure on the right (Fig. 5b) shows the time averaged PIV measurement of the steady jet flow. For this measurement, 500 image pairs were used in the time averaging. The maximum velocity magnitude is on the order of 100 m/s. The jet spreading and velocity decay are seen in the figure. Although the jet flow appears to be roughly symmetric near the exit, the symmetry vanishes further downstream. This is mainly because the fluidic actuator used to generate the steady jet flow was not a perfect setup to produce a turbulent jet typically seen in the literature [11].



(a) **(b)**

Fig. 5. PIV images generated using the seeder: (a) raw PIV image and (b) the time averaged velocity field [9].

The second case to assess the seeding capability of the present seeder utilized an unsteady jet out of a fluidic actuator. Fluidic oscillators, sometimes referred to as sweeping jet actuators, were adapted from the early fluidic amplifier designs and have been used as active flow control actuators. These actuators have been proven to be simple and highly effective actuators not only in lab scale studies (e.g., tested on the NASA hump model [12] and 10% scale NASA CRM-HL model [13]) but also in the full-scale testing of a vertical tail [14], as well as in the flight testing on the Boeing ecoDemonstrator [15]. One of the distinct features of these actuators is that they emit spatially and temporally oscillating jets without having any moving components. As depicted in Fig. 6a, the steady flow entering the actuator sweeps back and forth between the exit-side walls generating highly unsteady jets at the exit. Note that the internal and external flow fields of the fluidic actuators, which have been extensively studied in the literature, are not the focus of this study. Instead, this section demonstrates the applicability of the present seeder for unsteady high-pressure flows.

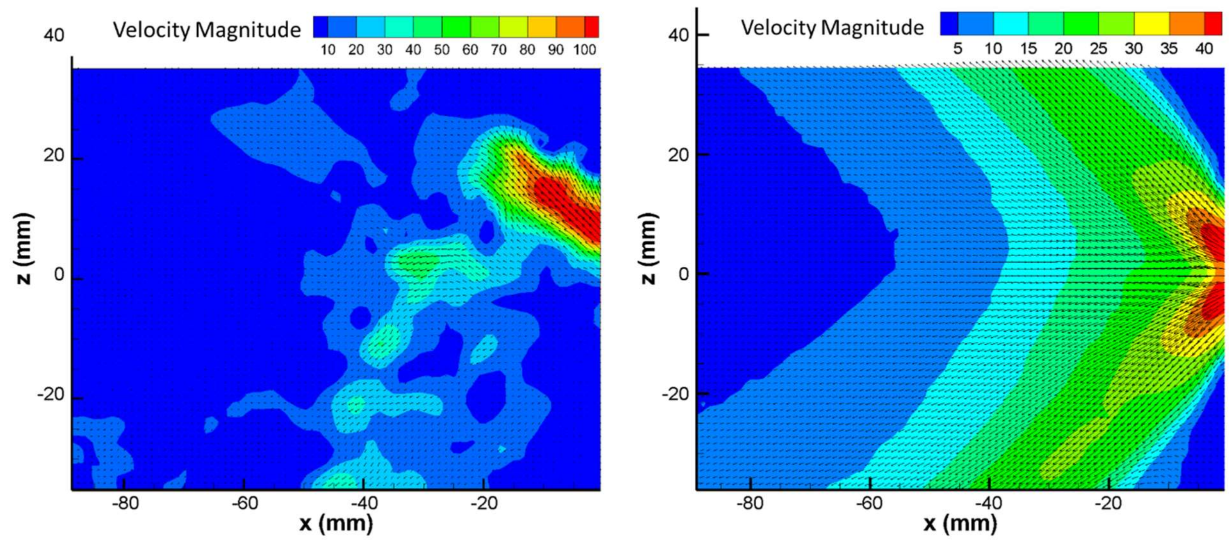


(a) (b)

Fig. 6. (a) Fluidic oscillator schematic and (b) particle seeding downstream of a fluidic oscillator.

The experimental setup for the oscillating jet was similar to the steady jet flow configuration. The fluidic actuator was operated in its normal mode where the jet oscillates at the exit. The flow rate to the actuator was 0.01 lb/s. At this flow rate, the jet oscillation frequency was measured to be 225 Hz. As mentioned before, the particle size of the seeder was analyzed with a spectrometer and the typical diameter was 1.2 μm. The Stokes drag analysis [16] indicates that the particles have approximately 3 millisecond relaxation time. Therefore, we can assume that the particles follow the oscillatory flow with negligible lag. The raw PIV image Fig. 6b shows the instantaneous particles at the actuator exit. The particle distribution appears to be uniform without having excessive intensity from larger particles. As expected, we see higher particle density near the actuator exit that spreads downstream. It is known that the oscillating jet has higher spreading rate than a steady jet. Therefore, we see more spreading in the traverse direction compared to the steady jet case. An instantaneous flow field obtained by postprocessing the raw PIV image pair is presented in Fig. 7a. As shown in this figure, the fluidic oscillators generate a highly complex flow field similar to wind gust and characterized by regions of locally accelerated flow along with small vortices. The time averaged flow field of the fluidic oscillator is shown in Fig. 7b. In order to capture the oscillating flow field, 2000 randomly sampled image pairs were used in the time averaged measurement. The regions of localized accelerated flow are no longer seen in the

flow field as the time averaging smooths them out. The time average velocity field shows a jet distribution with double peaks, typical of a fluidic oscillator jet. The jet velocity profiles at distinct downstream locations were also measured with a hotwire anemometer (see Ref. [9]). Although not shown here, the good agreement in the hot-wire and PIV results confirms the applicability of the present seeder, even for highly unsteady jets.



(a) **(b)**

Fig. 7. (a) Instantaneous and (b) time averaged velocity fields of the fluidic oscillator [9].

Suggestions for Future Work

The present seeder was designed and successfully tested for limited cases. There are many parameters that could be investigated for a desired particle distribution. Here are some suggestions to improve the seeder design:

- The particle density depends on the heater element and its surface area. More particles could be generated by increasing the heater surface area or using arrays of heater elements. The heater elements could be designed to be regulated with a simple knob as we see in typical fog machines.
- In our limited testing, we noticed that the particle size distribution can be varied by increasing the current for the same heater element. Therefore, more precise particle size adjustment is possible.
- In the current design, the particle transport to the working flow is mainly due to buoyancy force, where the heated air and the particles rise and are entrained by the flow. A venturi constriction could also be used at the Tee fitting to suck more particles into the working flow.
- In the current design, the seeder is installed vertically and appears as a deep cavity. A small portion of the incoming compressed air could be diverted into the chamber to increase the transport rate of particles to the working flow. Although we did not have heating issues, this could also help for consistent heat generation.
- In our limited testing, we did not notice too many larger-size particles. However, it could be possible for certain cases. In order to eliminate the larger particles, the small portion of the incoming flow could be used. The parallel line could be connected to the chamber tangentially. The tangential flow would create swirling flow inside the chamber where the larger particles would impact onto the chamber sidewall due to the circumferential force.
- In this design, the wick was used to transport fog fluid to the heater element and generated a sufficient number of particles. If needed, a larger wick could be used. A larger wick could

transport more fog fluid in theory; however, the capillary force only replaces the evaporated fluid. In addition, the chamber could be built under the reservoir to take advantage of the gravitational force to transport more fluid. However, it should be noted that the gravitational force would cause the fog fluid to drip constantly, even when the seeder is not in use.

- If the seeder is not installed vertically, then some type of seal between the reservoir and the chamber is needed.

Summary

There are many particle-based measurement techniques available for nonintrusive testing of the complex flows. Although commonly found in the engineering systems, the application of these particle-based measurement techniques is limited for high-pressure airflows. This is mainly because the high static pressure presents practical problems for introducing seeding particles, which is required for the particle-based measurement techniques. A new particle seeder design was proposed for the high-pressure airflows. This seeder produces fine particles using the condensation principle similar to theatrical fog machines. The seeder includes a heating element, a reservoir, and a wick. The heater vaporizes the fog fluid that then condenses into fine droplets. The droplets (i.e., particles) are entrained by and mixed with the airflow. In this design, the wick transports fog fluid to the heater element; therefore, the present design does not require a pump (i.e., no moving parts).

A sample seeder unit was built using readily available parts in a laboratory. First, the particles generated by the seeder were analyzed using a spectrometer and compared to those of a commercial fog machine. The spectrometer results indicated that the seeder generates particles with a typical diameter of 1.2 micrometer. Then, the seeder was attached to a fluidic actuator and the feasibility of the seeder was assessed in measuring the jet flow field. The seeder was tested for two different configurations. In the first case, the fluidic actuator was operated in a steady mode to emit a steady jet from the actuator. In the second test case, the actuator was operated in an unsteady mode to emit an oscillating jet at the actuator exit. With the help of the new seeder, the PIV measurements of the steady and unsteady flow field of the fluidic actuator were successfully obtained. The new seeder appears to be a viable solution for seeding and hence enabling particle-based measurement techniques for certain high-pressure airflows.

References

1. Adamczyk, A. A. and Rimai, L. "2-Dimensional Particle Tracking Velocimetry (PTV): Technique and Image Processing Algorithm," *Experiments in Fluids*, Vol. 6, 1988, pp. 373.
2. Adrian R J and Yao C-S “Pulsed Laser Technique Application to Liquid and Gaseous Flows and The Scattering Power of Seed Materials”, *Applied Optics,* Vol. 24, 1985, pp. 44–52.
3. Durst F., Melling A. and Whitelaw J. H., Principles and Practice of LDA, Academic Press, 1976, New York.
4. Melling, A., “Tracer Particles and Seeding for Particle Image Velocimetry”, *Measurement Science and Technology*, Vol. 8, No. 12, 1997, pp. 1406–1416.
5. Meares, A. J., Holdø, A. E., and Wakes, S. J., "A Novel Seeding Technique for The Flow Visualization of Pressurized Air Flows." *Measurement Science and Technology*, Vol. 8, No. 10, 1997, pp. 1183.
6. Acharya, A. S., Lowe, K. T., Ng, W., Danehy, P., “Seeding Mechanism for High-Pressure Nozzles”, AIAA Paper 2021-1068, Jan. 2021.
7. Acharya, A., Lowe, T., Ng, W., Danehy, P. M., Edquist, K. T., Burns, R. A., and Pham, H. "Seeding Method for Velocimetry and Visualization of Supersonic Retropropulsion Nozzle Plumes," AIAA Paper 2022-0915, Jan. 2022.
8. Hamdi, M., Havet, M., Rouaud, O., & Tarlet, D. “Comparison of Different Tracers for PIV Measurements in EHD Airflow”, *Experiments in Fluids*, Vol. 55, No. 4, 2014, pp. 1-12.
9. Koklu, M. and Pack Melton, L. G. "Sweeping Jet Actuator in a Quiescent Environment," AIAA Paper 2013-2477, June 2013.
10. Scarano, F. and Riethmuller, M., “Advances in Iterative Multigrid PIV Image Processing”, Experiments *in Fluids Supplemental*, Vol.29, 2000, pp. S51–S60

11. Gutmark, E., and Wygnanski. I. "The Planar Turbulent Jet." *Journal of Fluid Mechanics*, Vol.73, No. 03, 1976, pp.465-495
12. Koklu, M. "Application of Sweeping Jet Actuators on The NASA Hump Model and Comparison with CFDVAL2004 Experiments." AIAA paper 2017-3313, June 2017.
13. Pack Melton, L.G., Lin, J.C., Hannon, J., Koklu, M., Andino, M. and Paschal, K.B., "Sweeping Jet Flow Control on The Simplified High-Lift Version of The Common Research Model." In AIAA paper 2019-3726, June 2019.
14. Andino, M.Y., Lin, J.C., Washburn, A.E., Whalen, E.A., Graff, E.C. and Wygnanski, I.J., "Flow Separation Control on A Full-Scale Vertical Tail Model Using Sweeping Jet Actuators." AIAA paper 2015-0785, June 2015.
15. Whalen, E., Shmilovich, A., Spoor, M., Tran, J., Vijgen, P., Lin, J. C.,and Andino, M., “Full-Scale Flight Demonstration of an Active Flow Control Enhanced Vertical Tail,”, AIAA Paper 2016-3927, June 2016.
16. Adrian, R. J., and Westerweel, J., Particle Image Velocimetry, Cambridge University Press, New York, 2011.